PAM 629.139.85
YODER

CORPS OF ENGINEERS, U. S. ARMY

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS

(A REVIEW OF METHODS)

by

E. J. Yoder
Delon Hampton

Contract No. DA-19-016-ENG-2625

TECHNICAL REPORT NO. 73

Under Contract With

Arctic Construction and Frost Effects Laboratory
U. S. Army Engineer Division, New England
Waltham, Mass.

for

Office of the Chief of Engineers
Airfields Branch
Engineering Division
Military Construction

LIBRARY
BOREAL INSTITUTE
MAY 1 1961

June 1960

POLAR
PAM
4713
POLARPAM

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the "clinodographe," which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the "clinodographe," which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the "clinodographe," which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the "clinodographe," which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the ''clinodographe,'' which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the ''clinodographe,'' which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the ''clinodographe,'' which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

Arctic Construction and Frost Effects Laboratory, U. S. Army Engineer Division, New England, Waltham, Massachusetts

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS (A REVIEW OF METHODS), by E. J. Yoder and Delon Hampton. June 1960, 14 pp - illus, Appendices A and B - illus (Technical Report No. 73), Contract No. DA-19-016-ENG-2625

Unclassified Report

A discussion and evaluation are presented of the various techniques which may be adopted for measuring pavement profiles and pavement roughness. A summary bibliography of available pertinent literature is included as Appendix A. Abstracts of several articles appearing in the literature are included as Appendix B.

None of the instruments reviewed are completely satisfactory and a recommended device is outlined and discussed. This instrument is essentially the same as the ''clinodographe,'' which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two very small wheels of short wheel base.

UNCLASSIFIED

1. Pavements--Surface measurement methods
2. Pavements--Trafficability

I. Arctic Construction and Frost Effects Laboratory
II. E. J. Yoder
III. Delon Hampton
IV. Contract No. DA-19-016-ENG-2625

CORPS OF ENGINEERS, U. S. ARMY

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS

(A REVIEW OF METHODS)

by

E. J. Yoder
Delon Hampton

Contract No. DA-19-016-ENG-2625

TECHNICAL REPORT NO. 73

Under Contract With

Arctic Construction and Frost Effects Laboratory
U. S. Army Engineer Division, New England
Waltham, Mass.

for

Office of the Chief of Engineers
Airfields Branch
Engineering Division
Military Construction

June 1960

ARMY-MRC VICKSBURG, MISS.

PREFACE

This report presents the results of a review and study of available methods for the measurement of pavement profiles and pavement roughness conducted by the Purdue Research Foundation under an extension of Contract No. DA-19-016-ENG-2625 with the Arctic Construction and Frost Effects Laboratory of the U.S. Army Engineer Division, New England, Waltham, Massachusetts. These studies were conducted for the Office, Chief of Engineers, Department of the Army, Airfields Branch, Engineering Division, Military Construction, as a part of a continuing program for the development and evaluation of design criteria for construction in arctic and subarctic regions and areas of seasonal frost.

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS

(A Review of Methods)

TABLE OF CONTENTS

PARAGRAPH	TITLE	PAGE
	PREFACE	ii
	SYNOPSIS	v

PART I - INTRODUCTION

PARAGRAPH	TITLE	PAGE
1-01	Background	1
1-02	Purpose and Scope	1

PART II - STATEMENT OF PRINCIPLES

PARAGRAPH	TITLE	PAGE
2-01	Fixed Horizontal Plane Over Short Distances	3
2-02	Multiple Wheel Devices	3
2-03	Inertia	3
2-04	Accelerometers	3
2-05	Fixed Horizontal Plane Over Large Distance	3
2-06	Fixed Vertical Plane	4
2-07	Photogrammetric	4

PART III - DISCUSSION OF METHODS

PARAGRAPH	TITLE	PAGE
3-01	Fixed Horizontal Plane Over Short Distance	5
3-02	Multiple Wheels	6
3-03	Inertia	6
3-04	Accelerometers	7
3-05	Fixed Horizontal Plane Over Large Distance	8
3-06	Fixed Vertical Plane	9

PART IV - ANALYSIS OF ROUGHNESS MEASUREMENTS

PARAGRAPH	TITLE	PAGE
4-01	Methods of Approach	11
4-02	Power Spectral Density	11

TABLE OF CONTENTS (CONT'D)

PARAGRAPH	TITLE	PAGE
	PART V - CONCLUSIONS AND RECOMMENDATIONS	
5-01	Conclusions	13
5-02	Recommendations	14
	APPENDIX A: BIBLIOGRAPHY	
	APPENDIX B: REVIEW OF SPECIFIC METHODS	

LIST OF FIGURES

FIGURE NO.	DESCRIPTION	
1	Effect of position and wheel base on straightedge movements	6
2	Error due to wheel base	9
3	Schematic diagram of recommended device	13

SYNOPSIS

The various techniques which may be adopted for measuring pavement profiles and pavement roughness are discussed and evaluated. A summary bibliography of available pertinent literature is included as Appendix A. Detailed descriptions of some of these techniques, and abstracts of several articles appearing in the literature, are given in Appendix B.

The basic requirements for profile and roughness measurements include mobility, rugged construction, accuracy of measurement, and usability of data. Since none of the instruments reviewed are completely satisfactory, a recommended device is outlined and discussed. This instrument is essentially the same as the ''clinodographe,'' which appears best to fulfill the desired functions, except that integration is performed electronically and the single scanning wheel is replaced by two small wheels of very short wheel base. A similar machine is presently being developed at the AASHO Road Test, Ottawa, Illinois, (January 1958) and liaison with AASHO regarding this device is recommended.

PART I - INTRODUCTION

1-01. Background. This report presents the results of a review of literature pertaining to methods available for measuring pavement profiles and pavement roughness.

For many years, engineers dealing with performance surveys of highway pavements have recognized the need for developing an instrument capable of making roughness measurements. In the early history of roughness measurements, straightedges and levels were used to obtain the desired information. These devices, for reasons to be discussed later, proved inadequate, which resulted in efforts to discover a more efficient means of obtaining roughness data. This search brought about the development of roughometers which were capable of making continuous measurements of roughness along the pavement.

Later developments utilized gyroscopes, pendulums, levels of all types, light rays, and other techniques. The purpose of each of these instruments was not only to measure pavement roughness but to obtain profiles of the surface as well. Each type of instrument has some advantages, but also each type has some limitation.

As part of a contract between the Arctic Construction and Frost Effects Laboratory (ACFEL-NED) and the Purdue Research Foundation, a study of pavement pumping has been made at Purdue University. Under terms of an extension of this contract, a study of methods adaptable for measuring pavement profiles and roughness was initiated in the fall of 1956. This latter study encompassed a review of published literature and an evaluation of the various techniques.

1-02. Purpose and Scope. Surface roughness in airfield pavements can manifest itself in several ways. First, small and abrupt changes in pavement elevation result in vibrations which may cause excessive stresses in moving aircraft. Second, airplane response to random input resulting from changes in pavement elevation over relatively large distances tends to cause porpoising of certain types of aircraft. Porpoising can be described as an undulation of the aircraft which builds up in intensity if the frequency and mode of the pavement undulations are critical. Porpoising results when surface irregularities are systematic in variance and can be defined, as regards aircraft response, in terms of average values which are expressed in terms of statistical theory.

Pavement roughness and undulations can be caused by several factors. First, construction techniques permit some variation from the design profile. Second, repeated loads, particularly in areas of channelized traffic, can cause pavement distortion by plastic deformation in one or more of the pavement components. A third cause can be differential frost heaving and subsequent settlement.

A single instrument capable of measuring roughness and undulations must possess the following characteristics:

1. The instrument should be capable of making a large number of measurements in a short time.
2. It should be relatively rugged to be adaptable to construction control.
3. The instrument should measure abrupt changes of the pavement surface as well as true grade over large and small distances from some datum.

A comprehensive review of the literature has indicated that most instruments in present use do not fulfill all of the above requirements. Most devices are designed primarily to measure either pavement roughness (roughometer), or abrupt changes in profile over short longitudinal distances (straightedge). As a result, a study was made of the principles involved in the design of several types of elevation meters, leveling devices, profilometers, and similar devices to assist in recommendations as to machines most easily adaptable for use in making the desired measurements.

PART II - STATEMENT OF PRINCIPLES

Techniques which can be adopted for making the desired measurements can be categorized as outlined in the following paragraphs.

2-01. Fixed Horizontal Plane Over Short Distances. Instruments which fall into this category include straightedges, and profilometers of all types. It should be apparent that measurements with this type of device are limited by the span length. Small changes in grade which occur over distances greater than the span length of the straightedge are extremely distorted. However, abrupt changes, such as at pavement joints, are accurately measured.

2-02. Multiple Wheel Devices. This group includes devices with three or more wheels connected in tandem. By measuring the angles between the longitudinal links between tandem wheels, it is possible to obtain a measure of the pavement profile. This is accomplished by a process of integration. One limitation is that the wheel links must be started in a horizontal position; and since the angles are integrated, small errors in measurements may cause cumulative errors to result.

2-03. Inertia. This device is one which when towed over a paved surface is assumed to stay in a relatively fixed plane because of its own inertia. Changes in elevation are measured by means of a floating wheel which follows the paved surface and deviates from the machine proper. The common roughometer is a device of this type. The apparatus functions quite satisfactorily for measuring pavement roughness but does not measure pavement profiles. Also, the assumption that the device remains on a fixed plane due to its inertia may not be valid for some pavements.

2-04. Accelerometers. Accelerometers have been used for determining pavement profiles. Since acceleration is the second derivative of distance with respect to time, changes in profile can be determined by these measurements. However, values of vertical distance obtained by this method are a function of time and, therefore, small changes in elevation over large longitudinal distances cannot be measured except at high velocities of the measuring vehicle. Inertia and frequency responses of the towed vehicle also have an effect.

2-05. Fixed Horizontal Plane Over Large Distance. This group includes primarily the use of ordinary engineer levels. The procedure is obviously one of the most accurate, but also time consuming. A new device, developed by the U.S. Air Force, which uses a collimated light source and a series of photoelectric cells shows considerable promise.

2-06. Fixed Vertical Plane. Instruments in this group include gyroscopes and pendulums. This technique involves towing a vehicle over the surface and then, by means of integration, obtaining a measure of the true pavement profile.

2-07. Photogrammetric. Techniques involved for this procedure are not fully developed at the present time; however, some exploratory work has indicated its feasibility. The method consists of obtaining low altitude photographs of the pavement surface. By means of a stereoplotter a contour map of the pavement surface is then obtained.

PART III - DISCUSSION OF METHODS

The following paragraphs constitute a discussion of the various methods that can be adopted for making pavement profiles and roughness measurements. A summary bibliography is included as Appendix A. Detailed descriptions of some of the methods, as well as detailed abstracts of articles appearing in the literature, are given as Appendix B.

3-01. Fixed Horizontal Plane Over Short Distance.

a. In the early history of roughness measurement, straightedges and levels were used to obtain the desired information. One type used by many highway departments was basically a perambulatory straightedge, 10 ft long. Its points of contact with the road surface were made through three small, solid-tired wheels, the two end wheels being fixed and the center one sliding in a vertical plane. As the instrument was pushed along the road surface, the center wheel moved up and down; when the deflection reached a set amount, contact was made and a bell rang.[3*]

b. Another type formerly used to measure highway roughness consisted of a wooden frame made of two parallel members to which cast-iron end wheels were attached. The indicator, which carried a steel roller, was swung from the frame at its mid-point, and two steel scrapers were attached to the indicator, one in front of and the other behind the roller. This instrument only measured deflections greater than 1/4 in.[4]

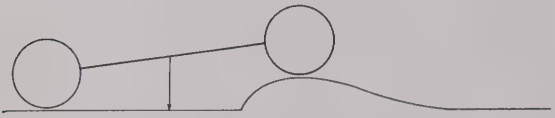
c. The type of profilometer used on the Bates Test Road in Illinois[1] consisted of a straightedge on a track 24 ft long, and a recording device which recorded autographically the profile of the pavement over which it passed. It was supported by bicycle wheels consisting of two wooden trusses 24 ft long by 20 in. high with a 3-in. space between them. Two turnscrews at each end permitted leveling the track at each setup, while a piano wire under constant tension, stretched from end to end, gave a datum for detecting any sag in the track. The recording apparatus consisted of an American strainagraph whose pen arm was connected by a rod with a brass wheel resting on the pavement surface. Thus, surface irregularities passed over by the small wheel were traced on the recording paper.

d. The profilometer used in the Arlington, Virginia, experiments, in 1923, had the recording apparatus riding on an angle iron, one end of which was fastened to a frame supported by two wheels which moved over the inner concrete curb of the circular track, while the other end was fastened to a steel-frame truck on four wheels carried by two iron rails. The profile of any transverse section of the roadways was secured by moving the recording apparatus along the angle iron, and that of any longitudinal section was secured by moving the entire frame along the tracks. The summation of vertical ordinates was given by an integrating attachment.

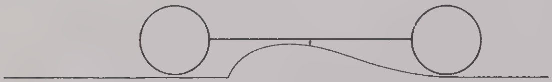
---

*Raised figures refer to references in Appendix A.

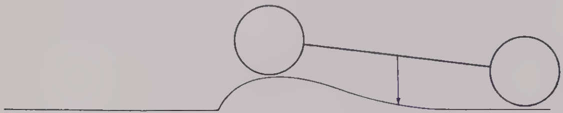
e. A recent development by the California Highway Department utilizes a mobile unit which records pavement roughness through compensating differential transformers.[57,58] This method, described in detail in paragraph 1-01, Appendix B, has many applications to pavement surveys, but it is believed that it will not yield the necessary data for airfield pavements. The primary limitation is length of wheel base. Figure 1 shows the effect of wheel base on these measurements.



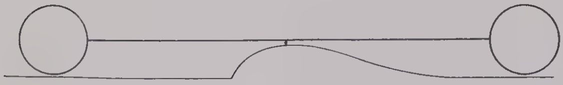
(a) PEN WILL RECORD DEPRESSION IN THIS POSITION



(b) PEN WILL RECORD TRUE DATA IN THIS POSITION



(c) PEN WILL RECORD DEPRESSION IN THIS POSITION



(d) PEN WILL RECORD TRUE DATA FOR LONG WHEEL BASE

Figure 1. Effect of position and wheel base on straightedge movements

f. A recent device known as the ''Hi-Lo Detector'' has been used with some success in the Midwest. This instrument makes it possible to obtain rapid measurements. It is made of aluminum and is available in lengths up to 16 ft.

This group of instruments will record quite accurately small changes in elevation such as faulted joints, and thus they have much application, especially for construction control. They will not, however, measure pavement profiles.

3-02. Multiple Wheels. The principle of this method was furnished by personnel of the AASHO Road Test, Ottawa, Illinois, and is described in detail in paragraph 1-02, Appendix B. This device used in conjunction with the common straightedge offers a possible procedure. A limitation of this technique is that of compensating for starting out on a slope.

3-03. Inertia.

a. The principal instrument in this category is the roughometer, which is a major improvement over the straightedge and level method of measuring roughness, since it allows work to proceed much more rapidly. The first instruments of this type were attached to the frame of an automobile. This made the results obtained dependent upon the automobile; thus, the instruments were not standardizable.

The most noteworthy of these instruments was the Dana Automatic Roughometer developed by Homer J. Dana.[15] Besides measuring the roughness, it also recorded the integrated roughness automatically as it did the mileage.

b. Realizing the limitations of the type of instrument described above, the Bureau of Public Roads introduced in 1940 standardizable equipment for measurement of road roughness.[27] This equipment, described in detail in paragraph 1-03, Appendix B, operates on the principle of the measurement of the vertical oscillation of a wheel suspension with respect to its supported frame.

This instrument is known as the ''roughometer'' and has found great favor with various highway departments besides being used extensively by its inventors. It is used abroad by the Road Research Laboratory in England. However, the instrument as now designed cannot be used for measuring the profile of a pavement.

c. Shortly after 1948, the Institute of Transportation and Traffic Engineering, University of California, Berkeley, conducted extensive research, under Professor R. A. Moyer, in roughness measurement.[39] The measuring instrument was primarily a Bureau of Public Roads roughometer with certain modifications – the major changes being an electronic oscillograph attachment and calibration equipment. This modified roughometer is called an ''electronic viagraph''; besides measuring the roughness, it presents it graphically in the form of a surface profile.

The viagraph is purported to measure roughness of any height up to approximately 3 in. with length limits from nil to around 20 ft. With further research, this instrument could be used for determining the profiles of airport pavements.

Roughometers will give reliable roughness measurements but will not measure pavement profile.

3-04. Accelerometers. The accelerometer used on the Bates Test Road was designed by the Bureau of Public Roads and utilized the recording section and case of an American strainagraph.[1] This instrument is described in detail in paragraph 1-04, Appendix B. The pen arm was attached to a rod supporting a weight suspended between two compression rings. The rod was attached directly to the rear axle of a motor truck by means of three steel rods. The recording paper moved a distance proportional to that passed over by the wheel. The roll carrying the paper was driven by a speedometer cable and a small rubber-tired wheel, which was rotated by contact with the rim of a rear wheel of the truck.

The compression of the springs could be varied by moving the guide bar either up or down which made the instrument adaptable for use on surfaces of varying roughness. The record was a straight line unless the weight in the instrument changed its position with respect to the axle. Also, any vertical acceleration caused the weight and consequently the pen to vary from a straight line.

The variation is a measure of the force which causes it, and the force corresponding to any particular variation could be determined by calibrating the springs. Knowing this force, and the mass of the wheel and axle, it was possible to compute the corresponding impact.

It is quite possible that an accelerometer could be designed which would automatically record the profile of a pavement. The main obstacle to be overcome is devising an instrument that would be sensitive enough to detect and record small changes in profile. In addition, measurements by accelerometers depend on the speed of the measuring vehicle. This can be used to advantage if aircraft and motor vehicle response is to be calculated.

3-05. Fixed Horizontal Plane Over Large Distance.

a. Use of precise surveying instruments will yield accuracy of the highest order. The principal objection to this method is the time required to make a survey over a large area.

b. Hand-carried leveling devices, such as instruments which indicate differences in elevation by means of measuring the pressure head of water, present possibilities. Barometers also have some application but will not yield results which are considered accurate for pavement profile.

c. A device which measures pavement elevation and records the data on magnetic tape, described in detail in paragraph 1-05, Appendix B, offers great possibilities. Possible limitations include cost of the instrument and the need for resetting the instrument after surveying 2000 to 3000 ft of pavement.

At the present time (January 1958), just one of the above instruments is available at the Wright Air Development Command, Wright-Patterson Air Force Base. Therefore, it is not possible to estimate the cost of manufacture. This instrument is designed primarily to obtain data which can be used to calculate power output of a runway.

3-06. Fixed Vertical Plane. Instruments included in this group are those which measure slope angles from some fixed plane. Most easily adopted are those which utilize the simple pendulum or gyroscopes. This type of measuring device, two of which are described in detail in paragraph 1-06, Appendix B, has been used with great success[36, 37, 48, 50, 53, 55] for various types of profile measurements.

When using either pendulum or gyroscopes as a reference, it is necessary to use the principle of slope integration. To give satisfactory results the instrument must mechanize the following function:

$$\Delta y = \int_0^s \sin \theta \cdot ds$$

$$x = \int_0^s \cos \theta \cdot ds$$

where:

y = change in elevation from starting point
s = distance traveled along the ground
x = horizontal component of travel distance
θ = slope angle

Integration of these functions can be accomplished from discrete points obtained in the field, or by means of electronic computers.

The slope angle measured by a device will be a function of its wheel base (figure 2). Development studies of systems for terrain measurement[50] indicate that for sinusoidal waves the device will produce waves of less than 10 percent error when the wave length is more than four wheel-base lengths. Whenever a device of this type is subjected to sinusoidal waves of random lengths and frequencies, it is possible to correct to some extent for inadequacies by proper filters.

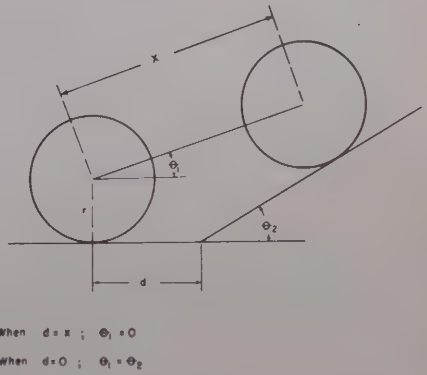


Figure 2. Error due to wheel base

The instrument which is most capable of making the desired measurements appears to be the clinodographe.[55] Other devices have been used quite satisfactorily, but this one has the advantage of combining profile measurements and roughness measurements. It has the disadvantage of using a relatively large wheel base (2.5 m).

PART IV - ANALYSIS OF ROUGHNESS MEASUREMENTS

4-01. Methods of Approach. Three methods of approach can be used for analysis of roughness data. The first of these consists of plotting discrete elevation points on profile paper. These data can then be reviewed with the end point of determining exact locations along a paved surface where the true profile deviates a fixed amount from the assumed.

The second approach is one in which roughness data are obtained (i.e. inches of roughness per unit of length traveled) and then this value is correlated with visual observations of the surface behavior of the pavement.

Roughness (or profiles) can be analyzed still a third way using a statistical approach. For this method the random input is expressed in terms of both frequency and amplitude. This latter method has the distinct advantage of application to either aircraft or vehicle response. Since roughness is important only insofar as it affects aircraft and vehicle characteristics, this approach deserves a great deal of attention.

Random input of a pavement, however, will be beneficial to the paving engineer only when an indication is given of the true point on the pavement where undue roughness is found. This will not indicate values of roughness which are detrimental.

The best method of approach is one that combines the first and third techniques. This involves plotting the true profile against longitudinal distance as well as analyzing the data statistically. Modern electronic computers can be used to great advantage for this last approach.

4-02. Power Spectral Density. A method used by Walls et al.[49] deals with random input with respect to time or distance. Buffeting of the aircraft as it travels along a pavement is essentially a random input with respect to distance. These inputs vary in a highly irregular manner and will be determined by frequency of input, amplitude of the wave, and speed of the aircraft.

If the runway roughness is a space disturbance, the power spectral density is expressed in radians per foot. The power spectral density of the disturbance y (x) is as follows:

$$\partial(\eta) = \lim_{x \to \alpha} \frac{1}{2\pi x} \left[\int_{-x}^{x} \gamma(x)\, e^{-i\eta x}\, dx \right]^2$$

This equation can be interpreted physically by the statement that the average power is the integrated sum of all the energies at all frequencies.

It will not be the purpose of this report to discuss the ramifications of these techniques. However, it should be brought out that to be of the utmost use, pavement roughness must be related to aircraft response. This can be accomplished by techniques described above.

PART V - CONCLUSIONS AND RECOMMENDATIONS

5-01. Conclusions. Basic requirements for profile and roughness measurements include mobility, rugged construction, accuracy of both profile and roughness measurements, and usability of the data. None of the instruments reviewed in this report are completely satisfactory in these respects without some modification.

The instrument known as the clinodographe appears to best fulfill the desired functions. Several limitations of this device require modification as follows:

a. The wheel base should be shortened, if possible.

b. Integration should be performed by electronic devices to insure accurate results.

Figure 3 shows a sketch of the device which is recommended for use. This machine is essentially the same as the clinodographe with one modification - the floating wheel is replaced with two small wheels of very short wheel base and can, in fact, be offset a small amount and thus overlapped. It is also similar to the device developed for terrain measurement.[50]

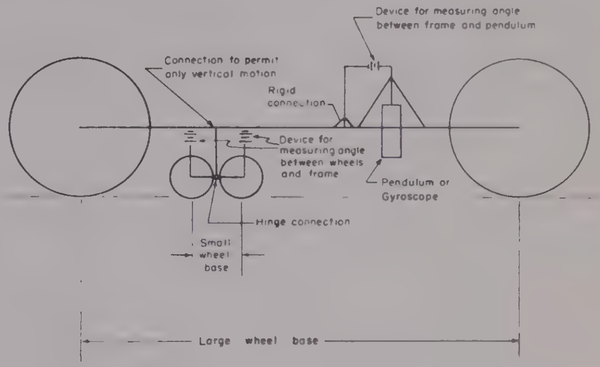

Device for measuring angle between frame and pendulum
Connection to permit only vertical motion
Rigid connection
Device for measuring angle between wheels and frame
Pendulum or Gyroscope
Hinge connection
Small wheel base
Large wheel base

Figure 3. Schematic diagram of recommended device

The pendulum arrangement would be utilized to reference the angular displacement of the towed frame. This can be accomplished by small differential transformers. The small wheels would each be referenced to the frame by transformers. Next the angular displacement of the two wheels can be referenced to the frame.

The transformer, which is mounted on the pendulum, can be circuited with those on the wheels to read directly the angle the chassis of the wheels makes with the horizontal.

Tendency for the floating wheels to leave the ground can be minimized by use of damping springs. Use of pendulums presents problems of oscillations. These, however, can be overcome by use of damping devices, or short heavy pendulums. Gyroscopes can be used to advantage so long as precession is controlled. This can be done by using gyroscopes with little friction. Another possible means of reference is through the use of heavy fly wheels. A detailed study of gyroscopes was not made, but they should present no problem.

Methods of measuring profiles have received great attention by personnel of the AASHO Road Test, Ottawa, Illinois. Research conducted by this organization has indicated the need for developing a device similar to that shown in figure 3.

5-02. Recommendations. On the basis of research reported herein, it is recommended that efforts be directed first toward purchase of the clinodographe, and that modification of this machine be made as outlined above. If this is not feasible, a machine could be developed which will perform the desired function.

Since a machine similar to that shown in figure 3 is being developed at the AASHO Road Test, it is further recommended that personnel at the test road be contacted for information regarding this machine. At the present (January 1958) work on this particular device is still in the development stage. However, information should be available by spring of 1958.

APPENDIX A: BIBLIOGRAPHY

1. Hogentogler, C. A., ''Apparatus Used in Highway Research Projects,'' National Research Council Bulletin, Vol. 6, No. 35, August 1923.

Presents apparatus used in highway research projects in the United States. The equipment is subdivided as follows: (1) apparatus used in investigations in the field of economic theory of highway transport, (2) apparatus used in the structural design of roads, and (3) apparatus used in investigations of materials. Two profilometers and one accelerometer, used to measure road roughness, are described; these are discussed in this report.

2. Public Roads, ''An Instrument for the Measurement of Relative Road Roughness,'' Public Roads, Vol. 7, No. 7, pp. 144-148, September 1926.

Bureau of Public Roads roughometer with instrument attached to the wheel of an automobile.

3. Andrew, H., ''Device Detects High and Low Spots in Concrete Road Surface,'' Engineering News-Record, Vol. 100, No. 4, pp. 161-162, January 26, 1928.

Straightedge used to measure road roughness.

4. Roads and Streets, ''Pavement Rater,'' Roads and Streets, Vol. 68, No. 3, p. 173, March 1928.

Device is a straightedge which measures deflections of the road surface exceeding 1/4 in.

*5. Badder, H. C., ''Review of Research, Experiment and Practice,'' Roads and Road Construction, Vol. 6, No. 64, pp. 107-109, April 2, 1928.

Roughometer attached to the wheel of a car used to measure road roughness.

6. Trainor, L. S., ''How Smooth Is a Pavement,'' Nation's Traffic, Vol. 2, No. 5, pp. 39-40, July 1928.

---

*Included as a matter of information; not perused in connection with this study.

See also, Good Roads, Vol. 71, No. 9, pp. 505-507, September 1928. A roughometer which automatically measures inequalities in pavement and makes permanent record of them is described. The device is attached to an automobile, and as the vehicle is driven over the pavement to be examined, every movement of the front spring is recorded. By calibrating the record traced by the instrument upon a strip of paper, the engineer is able to interpret the record in terms of the number of inches per mile.

Article also mentions the bumpometer – a straightedge measuring device for the determination of surface roughness developed by the Illinois State Highway Department.

7. Withycombe, Earl, ''Pavement Progress in California,'' Roads and Streets, Vol. 68, No. 7, p. 344, July 1928.

Prior to the time of this article the California Division of Highways had used an instrument, developed in New York State, known as the ''vialog'' to measure road roughness. However, by the time the article was written they had adopted the Bureau of Public Roads roughometer. (Description not available.)

8. Thompson, J. T., ''Effect of Pavement Type on Impact Reaction,'' Public Roads, Vol. 9, No. 6, August 1928.

The subject of this article is the effect of pavement type on impact reaction. The apparatus used in testing consisted of an impact machine for producing the necessary impact forces and an accelerometer for determining these forces.

9. Spielmann, P. E. ''Road Surfaces and the Mechanical Recording of Their Condition,'' Roads and Road Construction, Vol. 9, No. 99, pp. 76-78, March 2, 1931.

European and American instruments for examination and recording of irregularities of road surfaces are described. The first type mentioned was the Italian ''profilometer'' or odograph consisting of a metal frame, carried by sixteen wheels, and bearing at its center an indicating mechanism actuated by a small wheel in contact with the road surface. The instrument was hand-drawn over the surface to be measured.

The Danish Road Laboratory used two instruments for the examination of road surfaces. The first was a viagraph, but it was found that owing to its short length it was more accurate in the recording of irregularities of short wave length than of long. The instrument was not described in detail. The second type was a straightedge along which slid a recording apparatus consisting of a drum of paper and a pencil connected with the point traveling across the road surface.

*10. Railway Engineering, ''Railway Maintenance Problem,'' Railway Engineering, Vol. 52, No. 615, pp. 157-158, April 1931.

Instrument described which records difference in level between two rails of same track as well as superelevation on curves.

11. Murray, E. V., ''Bumps in Pavement Tested and Worked Automatically,'' Construction Methods, Vol. 13, No. 5, pp. 66-67, May 1931.

A ''profilometer'' designed by the Ohio State Highway Department which detects irregularities in surfaces and automatically marks them with white paint instead of producing a written record. It consists of four bicycle wheels upon which is mounted a straightedge, with an indicating wheel in the center. Depending upon the type of pavement being tested, the straightedge is either 10 or 18 ft long.

*12. Reynolds, J. G., ''Road Indicator,'' Transactions, Society of Engineers of London, pp. 117-121, 1931.

Instrument records the comparative draft on gradients.

13. Aughtie, F., ''A Remote Electrically-Recording Accelerometer With Particular Regard to Wheel-Impact Measurements,'' Physical Society of London, Vol. 44, No. 241, pp. 31-49, January 1932.

The instrument was developed for the measurement of the acceleration of the rear axle of a vehicle. The recording was done remotely and produced three records – two of acceleration and one of spring load. An oscillograph was used for taking the records.

14. Cardew, C. A., ''New Method of Automatically Locating Vertical Defects in Permanent Way,'' Railway Engineering, Vol. 53, No. 633, pp. 554-560, October 1932.

---

*Included as a matter of information; not perused in connection with this study.

Instrument invented to detect irregularities in the rails and mark them. Also measures deflections, under load, over a specified allowable amount.

15. Dana, H. J., ''The Dana Automatic Roughometer for Measuring Highway Roughness,'' Proceedings, Highway Research Board, Vol. 12, Part I, pp. 362-365, December 1932.

The instrument is a roughometer attached to the wheel of an automobile. A pencil operated through a pantograph system connected to a front wheel gives a continuous visible picture of the roughness of the road surface. An automatic stamping device records the mileage and integrated roughness every half mile. The record paper runs 5 in. per mile with a faster speed of 3 in. per 100 ft available for special roughness study.

16. Railway Gazette, ''Automatic Recording of Vertical Track Defects,'' Railway Gazette, Vol. 60, No. 16, pp. 774-777, April 20, 1934.

The device under consideration is the Stone-Cardew depression indicator which automatically records all vertical irregularities in track alignment that exceed predetermined limits.

17. Erb, A. K., ''Estimating Patching Volumes by Roughometer,'' Engineering News-Record, Vol. 116, No. 13, p. 451, March 1936.

A roughometer attached to the frame of an automobile is used to measure the roughness of pavements. From the data obtained, a determination of the volume of patching required can be made.

The instrument consists of a cylinder on a shaft equipped with an overrunning clutch. The clutch shaft is connected by a flexible shaft to a counter mounted on the dash. A drawstring connects the cylinder with an arm attached to the front axle, and the cylinder is provided with tension against the clutch and a brake to prevent overrunning the pull of the drawstring. The counter is of the setback type, and the unit is designed to record one unit for each half inch of measured roughness.

*18. Wilson, D. M., ''Safe Road Surfaces,'' The Surveyor and Municipal and County Engineer, Vol. 89, No. 2302, pp. 388a-b, March 6, 1936.

---

*Included as a matter of information; not perused in connection with this study.

Deals with treatment of existing surfaces, the materials employed for roughening purposes, and the testing of roughened surfaces.

19. Seitz, E. L., ''New Bumpograph Devised for Asphalt Concrete Pavements,'' California Highways and Public Works, Vol. 15, No. 2, pp. 26-27, February 1937.

Device consists of a wooden frame hinged in the middle, supported by a bicycle wheel at each end, and with two wheels at the middle hinge. No recording mechanism is used but bumps are marked by a crayon.

*20. Stradling, R. E., ''Road Research,'' The Surveyor and Municipal and County Engineer, Vol. 91, No. 2369, pp. 833-834, June 18, 1937.

Measurement of surface irregularities discussed.

21. Swinton, R. S., ''Measurement of Wear on Gravel Roads,'' Proceedings, Highway Research Board, Vol. 18, Part 1, pp. 323-328, 1938.

Procedure used in taking wear measurements consisted of reading a level rod to an accuracy of 0.01 ft on each foot of a cross section of the maintained road.

22. Montgomery, Julian, ''Pavement Surface Irregularities Studied,'' Roads and Streets, Vol. 81, No. 5, pp. 44-49, May 1938.

Article deals with pavement design. Surveying instruments are used to get vertical fluctuations in the test slabs.

23. Wilson, J. S., ''A Printing Method of Recording Road Surface Texture,'' Road Research Bulletin, No. 3, 1939.

Offset printing method used to determine the texture of a road.

24. Booth, Harris, ''Examination of Road Wear,'' Journal of the Society of Chemical Industry, Vol. 58, Part 1, pp. 501-507, 1939.

Describes methods used by the Road Research Laboratory for the examination and, where possible, the measurement of all forms of road surface deterioration. Methods

---

*Included as a matter of information; not perused in connection with this study.

included are texture paint and stone sweeping used in wear measurements and a 16-wheel carriage mounting a profilograph used to measure surface irregularity. The main components of this assembly are (1) the profilograph which gives a record of the profile of the road, (2) the rise integrator which is essentially a profilograph with a ratchet mechanism constructed so that when it rises the profilograph rises, but remains at a constant level when the profilograph falls, and (3) a classifier which counts the number of these rises between successive fixed amounts.

*25. Grossjohann, C., ''Measurement of Road Surface Roughness,'' The Surveyor and Municipal and County Engineer, Vol. 96, No. 2477, pp. 45-46, July 19, 1939.

Indirect and direct methods for determining the degree of roughness.

26. Moyer, R. A., ''Motor Vehicle Operating Costs and Related Characteristics on Untreated Gravel and Portland Cement Concrete Road Surfaces,'' Proceedings, Highway Research Board, Vol. 19, pp. 68-98, December 1939.

Operating cost of automobiles was related to the aforementioned types of road surfaces. Road roughness was measured by a Firestone comfort meter, and a profilometer. The Firestone meter is a sensitive recording type of multiple-element contact accelerometer. It records road roughness in terms of total vertical accelerations of the wheel of an automobile varying from 5 ft/sec to 55 ft/sec. The profilometer consists of a 10-ft straightedge and recording device; the profile is obtained by taking offsets.

27. Buchanan, J. A., and Catudal, A. L., ''Standardizable Equipment for Evaluating Road Roughness,'' Proceedings, Highway Research Board, Vol. 20, pp. 621-634, December 1940.

Article discusses the theory and design of the Bureau of Public Roads roughometer. This instrument is discussed in this report.

28. Public Roads, ''Standardizable Equipment for Evaluating Road Surface Roughness,'' Public Roads, Vol. 21, No. 12, pp. 227-234 and 243-244, February 1941.

---

*Included as a matter of information; not perused in connection with this study.

Article describes the physical make-up and functioning of the Bureau of Public Roads roughometer.

29. *Better Roads*, ''Improved Apparatus for Measuring Road Roughness,'' *Better Roads*, Vol. 11, No. 6, pp. 22 and 36, June 1941.

A review of the paper presented to the Twentieth Annual Meeting of the Highway Research Board by J. A. Buchanan and A. L. Catudal. (See reference 27.)

30. Hveem, F. N., ''Laboratory Builds Profilograph to Measure Pavement Roughness,'' *California Highways and Public Works*, Vol. 22, No. 3, 4, pp. 6-9, March-April 1944.

Instrument works on the principle of a fixed horizontal plane and employs 16 small, pneumatic-tired wheels, each of which is free to move independently in a vertical plane. The recording device mounted atop the profilograph automatically records the profile of the surface over which it passes. The instrument is hand-operated.

31. Inglis, C. E., ''Gyroscopic Principles and Applications,'' *Proceedings*, Institution of Mechanical Engineers, Vol. 151, pp. 223-235, 1944.

Gyroscopic principle and theory are explained and experiments presented with the aid of diagrams. Also practical applications of the gyroscope, in marine and aeronautical usage, are enumerated.

32. Davidson, Martin, et al., *Gyroscope and Its Applications*, London, Cheltenham Press, Ltd., 1946.

Deals with gyroscopic theory and its practical applications to marine and aeronautical problems. This publication is discussed in Appendix B.

33. Scott, W. J. O., ''Roads and Their Riding Qualities,'' *The Surveyor and Municipal and County Engineer*, Vol. 107, No. 2943, pp. 343-344, July 2, 1948.

Riding qualities of roads checked by the Public Roads Administration roughometer and by an instrument designed by the Road Research Laboratory. The latter is a 16-wheel, articulated carriage equipped with a profilometer, an integrator, and a classifier for measuring and recording the roughness. The profilometer records the longitudinal profiles, the integrator gives a rise length graph, and the classifier gives detailed particulars of individual irregularities exceeding various fixed amplitudes ranging from 0.1 in. to 1.5 in. This instrument works on the principle of a fixed horizontal plane and is hand-drawn at a slow walking pace.

34. Sheppe, R. L., ''Road Roughness Measurements on Virginia Pavements,'' Proceedings, Highway Research Board, Vol. 28, pp. 137-152, 1948.

Instrument used for obtaining measurements was a roughometer built from plans obtained from the Bureau of Public Roads.

35. Garland, Luke, and Kahn, Prediction of Dynamic Landing Loads, USAF Tech. Report No. 5815, January 30, 1949.

36. Kastrop, J. E., ''Sun Oil Company's Mobile Elevation Meter,'' World Oil, Vol. 128, No. 13, pp. 67-78 and 80, April 1949.

Device measures the difference in elevation between points on the earth's surface with the accuracy of a foot in several miles. Slope integration is the principle on which the elevation meter is based. This instrument is fully described in Appendix B.

37. Editor's Report, ''A Day With the Gyro Car on the L. and N.,'' Railway Engineering and Maintenance, Vol. 45, No. 5, pp. 673-675, July 1949.

Describes the methods and equipment used by the Louisville and Nashville Railroad to check the serviceability of its railroad track. A continuous graphic record of curvature and alignment, cross level and superelevation, surface variations in each rail independent of the cross level, the distance traveled, the elapsed time at any desired interval, and the location of mileposts and other landmarks is obtained. The Gyro Car is described in Appendix B.

38. Hughes, A. C., ''Riding Qualities of Road Surfaces,'' The Surveyor and Municipal and County Engineer, Vol. 108, No. 3010, pp. 614-618, October 19, 1949.

Article deals with road surfaces in general, and how they can be improved. It mentions the 16-wheel carrier developed by the Road Research Laboratory for the measurement of road roughness.

39. Western Construction, ‘‘Design and Uses of a Roughometer,’’ Western Construction, Vol. 25, No. 10, pp. 90-92, October 1950.

Primarily a Bureau of Public Roads roughometer, but certain modifications and additions - mainly an accurate and reliable electronic oscillograph attachment and calibration equipment - have been made. From the surface oscillograms provided by the oscillograph unit, the type of roughness encountered is determined. This roughness recorder section has been highly refined, and can be operated on any standard Bureau of Public Roads roughness equipment. Batteries or power supply, electronic circuits, and indicators are located inside the automobile used to tow the viagraph.

The calibration unit consists of a motor, gear box, connecting rod, and slider arrangement. Its function is to produce artificial bumps of varying length and height and at varying speeds.

The Bureau of Public Roads roughometer equipped with the aforementioned instruments has been given the name ‘‘electronic viagraph’’ by its developers at the University of California at Berkeley.

40. Abrion, Agrazion, and Pian, Effect of Structural Fluidity on Aircraft Loading, USAF Tech. Report No. 6358.

41. Moyer, R. A., and Shupe, J. W., ‘‘Roughness and Skid Resistance Measurements,’’ Highway Research Board Bulletin, No. 37, 1951.

Roughness and skid resistance experimental results are presented. The viagraph, as developed at the University of California at Berkeley, was used to make the roughness measurements. (See reference 39.)

42. Lewis, R. C., ‘‘The Design and Characteristics of a High Sensitivity Direct Current Operated Accelerometer,’’ Journal of the Acoustical Society of America, Vol. 22, No. 3, pp. 357-361, May 1950.

The design and characteristics of a high-sensitivity, direct-current-operated accelerometer are explained. The RCA type 5734 tube is used as the deflection-sensitive element. This instrument is discussed in Appendix B.

43. Better Roads, ‘‘Missouri Mechanics Build a Roughometer,’’ Better Roads, Vol. 21, No. 9, pp. 29-30, September 1951.

Bureau of Public Roads roughometer with an oscillograph which acts as a recorder. The recorder produces a chart of the vertical variation of the cumulative inches of roughness in the pavement.

44. Engineering, ''Vehicle for Recording the Condition of Railway Track,'' Engineering, Vol. 174, pp. 225-226, August 1952.

Article describes the Matisa-Mauzin track inspection car which was invented and is being used in France. It measures and records the rate of change of relative levels of the rails, vertical profile of the track, variation in superelevation, and variation in gauge.

45. Roads and Road Construction, ''Checking Road Surface Irregularities,'' Roads and Road Construction, Vol. 31, p. 219, August 1953.

Surface irregularities measured by a perambulatory straightedge, 10 ft long. Its points of contact are made through three small, solid-tired wheels, the end ones fixed, and the center one sliding in a vertical plane. As the instrument is pushed along the road surface the center wheel moves up and down. When the deflection reaches a set amount contact is made and a bell rings.

46. Smith, D., ''Six Uses for a Roughometer,'' Surveyor and Public Works, Vol. 85, No. 1, pp. 55-56, January 1954.

Six uses of the roughometer as regards its application to highway engineering are listed. (See reference 28.)

47. Walls, J. H., Houbalt, J. C., and Press, H., ''Some Measurements and Power Spectra of Runway Roughness,'' U. S. National Advisory Committee for Aeronautics, Tech. Note 3305, November 1954.

48. Sattinger, I. J., ''Methods of Evaluating the Effects of Terrain Geometry on Vehicle Mobility,'' Proceedings, Interservice Vehicle Mobility Symposium, U. S. Army, April 1955.

Methods of determining allowable speed over partially passable territory, and resistance to motion and available tractive effort for the case of nonuniform load distribution are discussed.

49. Houbalt, J. C., Walls, J. H., and Smiley, R. F., ''On Spectral Analysis of Runway Roughness and Roads Developed During Taxiing,'' U. S. National Advisory Committee for Aeronautics, Tech. Note 3484, July 1955.

Method of analysis of runway roughness data utilizing spectral analysis is presented. Procedure is based on a random input theory.

50. Sattinger, I. J., and Therkelsen, E. B., An Instrumentation System for the Measurement of Terrain Geometry, Land Locomotion Research Laboratory Research Report No. 4, 1956.

A vertical gyroscope is used to measure the profile of the ground over which the instrument travels. An electrical system, based on the slope integration method, is used to integrate and record the changes in slope. This instrument is discussed in detail in Appendix B.

51. Holloway, F. M., ''Road Roughness Measurements on Indiana Pavements,'' Thesis for MS in CE, Purdue University, June 1956.

Roughometer constructed from plans supplied by the Bureau of Public Roads was used to make the measurements. (See reference 28.)

52. Hardy, R. L., ''Pendulous Cantilever Principles Applied to Self-Leveling Instrument Design,'' Surveying and Mapping, Vol. 16, No. 3, pp. 292-298, July-September 1956.

The theory of the design of self-leveling instruments is discussed.

53. Sattinger, I. J., The University of Michigan Final Report on Terrain Geometry Measurement, No. 2384-13-F, DA 20-018-Ord-13754, April 1956.

Article discusses briefly the various systems of terrain measurement, gives an analysis of the slope integration method of determining the profile of a surface, gives the requirements of a terrain measurement system, proposes an experimental program for developing a terrain measuring instrument, and gives conclusions and summary of work performed. The methods discussed include the use of surveying instruments, the roughometer, the profilograph, the aneroid barometer, slope integration, aerial photography, sonic altimeters, and radar altimeters.

54. Better Curves, Catalog, American Railroad Curvelining Corporation, 137 Hollywood Ave., Douglaston L. I., New York, N. Y.

An apparatus which measures curves of railroads using the string line principle is described. This device is reported to give excellent results for railroad curve lining and suggests possibilities of adaptation to measurement of pavement profiles.

55. Simonin, Raymond F., ''Le Clinodographe,'' *Extrait De La Revue Générale Des Routes Et Des Aerodromes*, No. 255, April 1953.

    The clinodographe is a device which automatically measures and records road roughness and profiles. The device utilizes a cantilever; all integration is done mechanically without use of electronic instruments.

56. Ziui, S. M., and Wickerstom, P. D., *Development of a Method for Measuring Runway Roughness and Computing Airplane Response*, Wright Air Development Command, Tech. Note 56-222, 1956.

    A new device which measures pavement roughness accurately is described. This device operates on the principle of collimated light. A bank of photoelectric cells is towed along a runway. The collimated light is beamed along the longitudinal direction of the runway and deviations from this fixed horizontal plane are picked up by the photoelectric cells. The apparatus is designed to record changes on magnetic tape.

57. California Department of Public Works, Division of Highways, *Maintenance Manual for the Truck Mounted Profilograph*, 1956.

58. California Department of Public Works, Division of Highways, *A Preliminary Report on Measuring Pavement Roughness From Profilograms*, March 8, 1957.

PAVEMENT PROFILE AND ROUGHNESS MEASUREMENTS

APPENDIX B: REVIEW OF SPECIFIC METHODS

TABLE OF CONTENTS

PARAGRAPH TITLE PAGE

1-01 Fixed Horizontal Plane Over Short Distance (California Department of Public Works Profilometer) B1

1-02 Theory of a Three-Wheel Device for Determining Pavement Profile B1

1-03 High Mass or Inertia (Bureau of Public Roads Roughometer) B3

1-04 The Design and Characteristics of a High-Sensitivity Direct-Current-Operated Accelerometer B4

1-05 Fixed Horizontal Plane Over Large Distance (Development of a Method for Measuring Runway Roughness and Computing Airplane Response) B6

1-06 Fixed Vertical Plane (Pendulum and Gyroscope) B8

LIST OF FIGURES

FIGURE NO. DESCRIPTION

B1 Principle of compensating transformers B1

B2 California truck-mounted profilometer B1

B3 Principle of three-wheel drive B2

B4 Public Roads roughometer B4

B5 Kansas Highway Department profile device B8

B6 Trailer assembly of terrain geometry measurer B13

B7 Schematic diagram of the clinodographe B13

B8 Integrator of the clinodographe B14

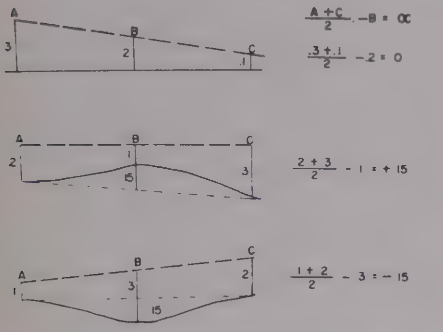
B9 The clinodographe B15

B10 Component parts of elevation meter B16

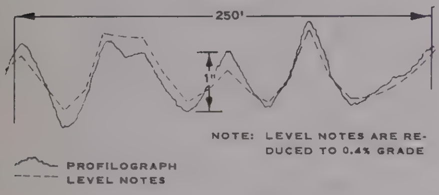
B11 Sun Oil Company elevation meter B17

APPENDIX B: REVIEW OF SPECIFIC METHODS

1-01. Fixed Horizontal Plane Over Short Distance (California Department of Public Works Profilometer).[57, 58] The device used by the California Highway Department is essentially a straightedge. However, modifications have been made in order that measurements might be obtained using compensating differential transformers. Figure B1 shows the principle of the compensating transformers while figure B2 is a view of the truck-mounted profilometer.



a. ALGEBRAIC SUMMATION OF TRANSDUCERS



b. PROFILOGRAPH LEVEL NOTES

Figure B1. Principle of compensating transformers

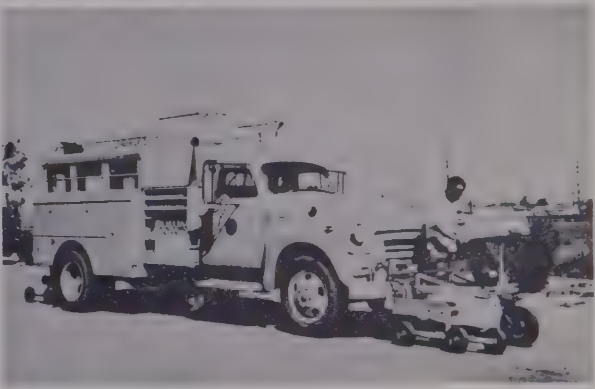


Figure B2. California truck-mounted profilometer

(Drawing and photo courtesy of California Highway Department)

This method of measurement has limitations as do most straightedge devices. It is capable of measuring bumps and other surface irregularities but will not measure true pavement profiles. If a device operating on the straightedge principle is turned over a uniform slope it will not record that slope.

The main advantage of this device is that it is able to use compensating transformers. Thus, pavement irregularities are measured and recorded automatically.

1-02. Theory of a Three-Wheel Device for Determining Pavement Profile.* The device consists of three wheels in a vertical plane, each of radius r, with centers connected by two rigid links, each of a length equal to $2\pi r$. Each link may rotate through small angles about the center of the middle wheel. The wheels are numbered 1, 2, and 3 from front to rear (figure B3).

---

*This method supplied by personnel of the AASHO Road Test, Ottawa, Illinois.

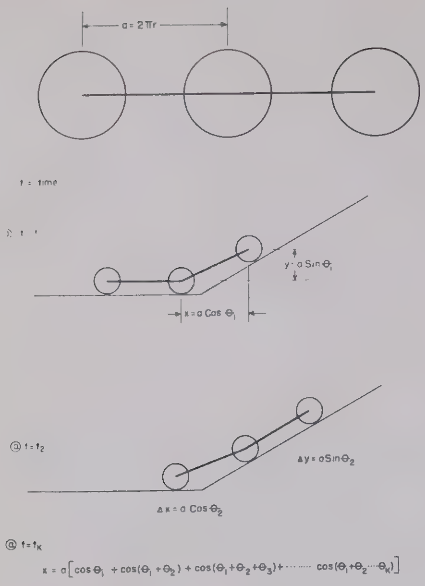


Figure B3. Principle of three-wheel device

Means are provided for measuring the angle of rotation of wheels 1 and 2, with respect to their rear links. (The rear link of a wheel is the link connecting the wheel to the next wheel to the rear.)

Wheel 2 is the driving wheel.

The device must be capable of performing certain functions which will become clear from the following analysis.

Let α = the angle through which wheel 1 (or wheel 2) rotates during a specified interval, measured with respect to link 1 (or link 2). α is always positive, and will equal 2π radians plus or minus a small fraction of a radian.

θ = the acute angle, at any instant, between the links. Positive θ is measured upward from link 1. It will usually vary between maximum and minimum values of about plus 2 degrees and minus 2 degrees.

Let t = time.

At t = 0 all three wheels rest on a level, plane surface of length = 2a. An origin of rectangular coordinates, x and y, is taken at the center of wheel 1 at t = 0. The x-axis is parallel and the y-axis perpendicular to the plane surface. Axes x and y are defined as the coordinates of the center of wheel 1 at any time, t .

The following is the sequence of events which occur during the determination of n + 1 points on the profile of the pavement, and the corresponding coordinates of the center of wheel 1.

Instant or Interval of Time	Event, and Simultaneous Values of x and y
0	Wheel 2 instructed to turn 2π rad. Wheel 1 instructed to measure α_1 . $x - y = \alpha = \theta = 0$.

0 to t_1	Wheel 2 turns 2π rad. Wheel 1 measures α_1.
t_1	θ_1 recorded. Wheel 2 instructed to turn α_1 rad. Wheel 1 instructed to measure α_2. $x = a \cos \theta_1, \ y = \sin \theta_1$.
t_1 to t_2	Wheel 2 turns α_1 rad. Wheel 1 measures α_2 .
t_2	θ_2 recorded. Wheel 2 instructed to turn α_2 rad. Wheel 1 instructed to measure α_3 . $x = a \cos \theta_1 + a \cos (\theta_1 + \theta_2)$ $y = a \sin \theta_1 + a \sin (\theta_1 + \theta_2)$

. . . . ;

t_{k-1} to t_k	Wheel 2 turns α_{k-1} rad. Wheel 1 measures α_k .
t_k	θ_k recorded. Wheel 2 instructed to turn α_k rad. Wheel 1 instructed to measure α_{k+1}. $x = a[\cos \theta_1 + \cos (\theta_1 + \theta_2) + \cos (\theta_1 + \theta_2 + \theta_3) + \ldots + \cos (\theta_1 + \theta_2 + \ldots + \theta_k)]$ $y = a[\sin \theta_1 + \sin (\theta_1 + \theta_2) + \sin (\theta_1 + \theta_2 + \theta_3) + \ldots + \sin (\theta_1 + \theta_2 + \ldots + \theta_k)]$
tn	θ_m recorded. x and y are obtained from the above formulas by substituting m for k .

The profile obtained as described above is actually the locus of the center of wheel 1. For practical purposes, the pavement profile may be obtained by subtracting r from each of the m + 1 values of y computed as described above.

1-03. High Mass or Inertia (Bureau of Public Roads Roughometer). The Public Roads roughometer consists of a single wheel (figure B4) which is towed by a vehicle. It is designed to operate in dynamic balance and not to be affected by the towing vehicle.

The instrument is constructed with a single pneumatic-tired wheel that has its axle attached to the center of two single leaf springs, one on each side of the wheel inside a rectangular frame. The springs are attached at their ends to the front and rear beams

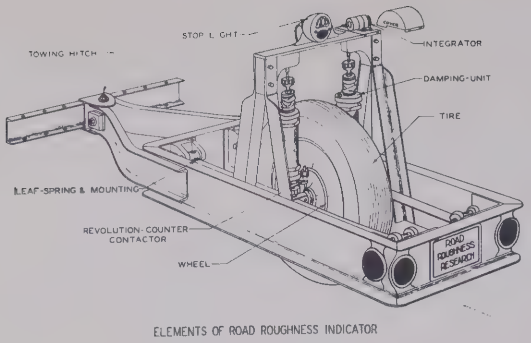


Figure B4. Public Roads roughometer

of the rectangular frame. The unit is connected to the towing vehicle by a tongue on the front of the frame. The integrator unit is mounted on a crossbar over the wheel, to which pistons of two dashpot spring damping devices are also attached.

To integrate the spring deflections that had occurred at any desired time, a commutator disk was built, in order to electrically operate the remote-recording unit. Six, equally spaced contacts and a single brush cause six closures of the electrical circuit that actuates the counter. The pitch circle of the cable drum that drives the commutator is 6 in. in circumference; therefore, each impulse to the electric counter marks the accumulation of 1 in. in the vertical movement of the axle with respect to the trailer frame. Distance traveled and vehicle speeds can be determined from the towing vehicle speedometer or with a stop watch and revolution counter on the instrument board.

As mentioned, the instrument measures roughness with respect to a fixed horizontal plane. The values obtained are vertical displacements of adjacent portions of the road surface and are usually recorded in inches per mile. The profile of the surface cannot be obtained because the instrument is limited to the measurement of vertical differences in adjacent portions of the pavement.

1-04. The Design and Characteristics of a High-Sensitivity Direct-Current-Operated Accelerometer.[42] The accelerometer under discussion uses the RCA 5734 tube as the deflection-sensitive element. The anode projects through a diaphragm at the tube end, and can be moved relative to the cathode by flexing the diaphragm – a simple accelerometer is obtained by adding a mass to the anode extension and using the diaphragm as the spring element. The moment of inertia of the mass system about the diaphragm center, together with the diaphragm stiffness, determines the natural frequency of the pickup, and mass movement about the diaphragm center determines the sensitivity to acceleration.

The weights consist of two nuts, of changeable size and screwed onto an extension member, which is spot-welded to the transducer anode. The g range of the pickup is that value required to cause the rated anode deflection. Damping is provided by means of selected fluids which are retained between the stop ring and the anode extension by capillary action. The inner case assembly is machined to a close fit in the protective case and is slotted to engage a pin in the case thus orienting the sensitive axis of the tube perpendicular to the mounting flange. The case pickup weighs only 2 oz.

Accelerometers of this design can be produced with a certain range of output sensitivity, which is associated with a limited range of natural frequency. Another important characteristic is that the g range and natural frequency range can be extended by modification of the weights and weight attachments.

This accelerometer is responsive to both linear accelerations and angular accelerations in its plane of sensitivity. The ratio of angular sensitivity to linear sensitivity is as follows:

$$\frac{S\alpha}{Sa} = \frac{\text{volts/rad/sec.}^2}{\text{volts/in./sec.}^2} = \frac{\gamma o^2 + Yo^2}{Yo} = Yc$$

γo = radius of gyration of the weighing system about its mass center

Yo = the distance of the mass center from the diaphragm

Yc = the distance from the diaphragm to a point mass.

This ratio should be low. Yc approaches Yo as a minimum, and it is therefore important to have a very close-coupled mass system.

The coupling parameter Yc can be expressed as a function of accelerometer sensitivity and natural frequency:

$R_x = M_o\ (\gamma o^2 + Yo^2)\ (2nf_n)^2$, and

Rx = MoYog (St/Sa), where

R = rotational stiffness of the diaphragm in lb-in./rod

St = transducer sensitivity in volts/rod

Equating the two above, we find:

$$Yc = \frac{\gamma o^2 + Yo^2}{Yo} = \frac{g}{(2\pi)^2} \times \frac{St}{Safn^2}$$

Yc values for this design range from 0.3 to 0.5 in.

The ability of the accelerometer to measure the component of a linear acceleration acting in its sensitive direction correctly is a function of the deflection sensitivity of the transducer, the uniformity of the diaphragm stiffness in all planes through the tube axis, and in the parallelism of the principal inertial axes of the weighing system with the tube axis.

Accelerometers are usually damped to 65 per cent of critical, causing the phase shift to be approximately linear, varying from zero at low frequencies to 90° at the undamped natural frequency. This characteristic allows undistorted representation of wave shape.

The stability of the dynamic sensitivity is very good. Under the operating conditions selected for the accelerometer the sensitivity is changed by only 5 per cent over a heater voltage range of 5.5 to 7.5 volts.

The pickup impedance is of the order of 125,000 ohms and the frequency range low, allowing the use of very long cables without effect on frequency response. Also this instrument may be used with galvanometer-type recording oscillographs.

The accelerometer is used primarily as a recording device, but occasionally it is used as a combination measuring-recording device. An illustration of the latter is the Firestone comfort riding meter which records road roughness in terms of total vertical accelerations.

1-05. Fixed Horizontal Plane Over Large Distance. (Development of a Method for Measuring Runway Roughness and Computing Airplane Response.[56]) The instrument described herein was developed by Mid-West Research Institute for the Wright Air Development Command, Wright-Patterson AFB, Ohio. This instrument works on a fixed horizontal plane principle and uses a collimated light source. Descriptions of each of the component parts are as follows.

a. Reference. A highly mobile, collimated light source, adjustable through a small angle in elevation. It is required that this remain horizontal over long distances. This unit consists of:

1. Two-wheel trailer.

2. Collimator.

3. Light source.

4. Bore sighting system.

5. Power supply.

b. Projector Cart. This consists of a two-wheel trailer which is stationed at one end of the runway or taxiway.

c. Collimator. The collimating unit is a standard USAF F-83 collimator with a 4.25-in. collimating base and a 66-in. collimating tube.

d. Light Source. An arc lamp (100 watts and 80 candle power) is focused through a condensing lense and then through a pinhole of 0.01-in. diameter. This results in a light beam about 1/3 the diameter of the source.

An exterior adjustment is provided to move the pinhole longitudinally to permit minor changes in temperature. A disc is rotated by motor in front of the light at 600 cycles per minute to permit improvement of signal to rise ratio.

e. Leveling System. The light source is aimed much as a gun sight by means of a special bore sighting device mounted on the side of the trailer. This does not imply a level sight but rather an assumed plane, not necessarily horizontal, from which reference is measured. By trial and error, tilt and azimuth of the light are adjusted for the range of the profilometer. This is accomplished first by means of a target, and then a trial run is made to make certain the profilometer will pick up the light for the desired length.

f. Power Supply. Power for the light source consists of 48-volt wet batteries, and for the synchronous motor, a 60-cycle, 115-volt generator.

g. Profilometer. A cart with the servo-optical system consists of a balanced photoelectric sensing head riding on a vertical ball-bearing track under the direction of a servomotor drive system. The servomotor receives its energy from a servoamplifier which receives energy from the photo cells.

This system makes certain the photocells are always centered on the light source. The position of the bank of cells is translated through gearing with the servomotor into proportional rotation of the rotor of the digitizer unit.

The profilometer is mounted on springs to reduce the frequency response requirements of the servomechanism by filtering out high frequency variations of pavement. In other words, true roughness is filtered out and only large undulations are measured. To compensate for difference in relative elevations of the electric cells and runway (due to spring, tires, etc.) a follower is hooked into the servomechanism to compensate for changes.

h. Beam Sensing System. This consists of a 5-in. × 10-in. × 14-in. aluminum box

(5-in. × 10-in. faces light) guided by a lugged rubber belt. The light is then viewed by an array of photoelectric cells. Six cells are used, one on each side provides a signal for horizontal alignment. The remaining four are in four quadrants and position the bank to the light power delivered. The position of the bank of cells is measured by servomotors.

i. Servo System. An odometer wheel is hooked in for distance.

j. Digitizer System. This is manufactured by Austin Co. This unit permits 360-degree revolution of a shaft to be resolved to one part in 2,000.

k. Data Recording System. A Davies Laboratory special magnetic tape recorder is utilized. It is desired to use these data on both digital and analog computers. Therefore, it is desirable that word separation be proportional to distance.

For this system the words are 0.25 in. apart corresponding to 1/2 of the runway. To accomplish this the odometer wheel is coupled electrically to the tape speed so that they are synchronized. Thirteen channels are used for the device. Twelve channels are for recording and one channel is for ‘‘marking.’’ The tape may be played back at a speed of 30 in. per second on the same unit.

The output pulses must be amplified and sharpened. At the present time the amplification is too great and thus too much noise results. The instrument can only get one or two words back at the present time. This machine can be towed about 2,000-3,000 ft before resetting the device.

At the present stage of development discrete profile points cannot be obtained. However, the device could be modified to accomplish this.

1-06. Fixed Vertical Plane. (Pendulum and Gyroscope).

a. Kansas Highway Department Profilometer. The sensing unit for this machine is mounted on a light trailer while the recorder is designed to be mounted in the towing vehicle (figure B5).

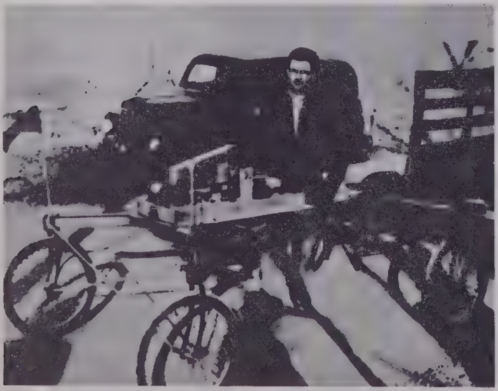


Figure B5. Kansas Highway Department profile device

(Photo by Kansas Highway Department)

The sensing element consists of a U-shaped tube partially filled with mercury. As the instrument is subjected to changes in slope, a servomechanism actuated by photoelectric cells continuously changes the position of the sensing element so as to keep the mercury at the same height in each arm of the tube. The angle between the sensing unit and the frame of the trailer is then integrated over the distance traveled by means of a ball-and-disc integrator.

Accuracy of this device is such that the indicated elevation may deviate from the true elevation as much as 2 ft per mile. Horizontal distances are slope distances but a marker is provided to tie the profile in with existing landmarks.

b. A Day With the Gryo Car on the L. and N.[37] The Gyro car is a track-inspection railroad car developed by the Chesapeake and Ohio Railroad in 1937.[37] It includes detecting and recording mechanisms which make a continuous graphic record of curvature and alignment, cross level and superelevation, surface variations in each rail independent of the cross level, the distance traveled, the elapsed time at any desired interval, and the location of mileposts and other landmarks. From the time and distance records the speed of operation at any point can be determined.

The recording mechanism is located in the center section of the Gyro car. The design is such that the car can be operated in either direction with equal facility, and accuracy of the record is not affected by any reasonable speed, or by rolling or nosing of the car body.

The basic unit of the recording mechanism is a table equipped with a roller carrying a 24-in. paper tape which continuously moves across the table at a rate directly proportional to the speed of the car. Seventeen pens are attached to the activating mechanisms. Eight of these are used to record the information listed above with the other nine functioning as follows: five form base lines; two form grading lines, 1/4 in. to one side of each of the two low-joint base lines; and two form other grading lines, 1/4 in. each side of the surface base line.

An essential element of the equipment is a two-wheel measuring and recording truck mounted under the car, midway between the end trucks, in such a way that it is free to move within wide limits, both vertically and horizontally, relative to the car body, and to tilt or rotate about its longitudinal axis. As these motions are imparted to it by the track, they are transmitted through suitable connections and actuate corresponding pens on the recording table, the magnitude of the variations from straight lines by the pen lines being in direct ratio to the amplitude of the movements of the truck.

Longitudinal movement of the truck relative to the car body, as rotation of the truck about its vertical axis, is restricted within very narrow limits.

Since the truck must be free to move laterally or vertically, or to tilt, it is not depended on to carry any of the weight of the car – just enough to keep it firmly on the track and to insure stability. It is also attached to the car in such a way that when it is displaced laterally it moves in a straight line and tends to return to its central position under the car.

The paper tape upon which the record of track conditions is made is driven from the wheels and axle of the truck by means of a system of gears and shafts.

The tendency of the truck to remain centered is utilized to record curvature. As the truck rounds a curve, the recording truck moves laterally, but always hugs the inside rail of the curve. This lateral movement is transmitted to one of the pens on the recording table, displacing it in a fixed ratio to the displacement of the truck.

Superelevation on curves and cross level on tangents are obtained by recording the transverse tilt of the truck. This motion is transmitted by means of a shaft and system of levers, through a gyroscope, to another of the pens on the recording table.

Surface variations are measured by the rise and fall of the center truck relative to the car frame. The value recorded at any instant is the difference in the elevation of the tops of the rails at the recording truck and the rail elevation at the centers of the end trucks.

Low joints are recorded independently of other surface variations by measuring the rise and fall of the middle pair of wheels in the six-wheel truck at the rear of the car. The motion of each wheel is transmitted by means of a hydraulic system directly to a recording pen.

Time and distance are recorded at 20-sec and 100-ft intervals, automatically. The locations of landmarks and mileposts are recorded by a pen that is controlled by two push buttons which are operated by observers at observation windows on opposite sides of the car, directly opposite the recording table.

c. The Gyroscope and Its Applications.[32] The simplest form of gyroscope consists of two distinct parts. The first is a wheel which has a relatively heavy rim for its size, and which is free to spin about its axis. The axle is mounted in a frame, and wheel and axle can rotate in this with a minimum of friction.

One of the most important concepts in the theory of gyroscopic motion is that of precession. The author defines this as follows: when a torque, equivalent to up-and-down forces, is exerted on the axle of a gyroscope, the motion of the ends of the axle of the gyroscope takes place, not in the direction of the forces as occurs when the wheel is not spinning, but in a direction at right angles to this direction. In simpler terms, precession may be thought of as the conical movement which the axis of spin of the gyroscope describes about a fixed direction, when the axis of spin is at an angle to that of the fixed direction. The change in the angle which the axis of spin makes with the fixed direction is known as nutation.

Precession takes place when the vertical through the point of support of the apparatus does not pass through the center of gravity. Also when precession has been established, the gyroscope would cease to fall if friction at the precession points could be entirely eliminated or counteracted by any means, i.e. a follow-up motor.

The theory of momentum and conservation of momentum are very important in the study of gyroscopic motion. Momentum is equal to the product of mass times velocity. The Law of Conservation of Momentum is stated as follows: In any system of particles, whether rigidly connected or not, the total angular momentum of the system relative to any point fixed in space remains constant, provided no external forces act on the system, internal forces only being considered.

The angular momentum of a system about a line in any direction can be resolved about a line in any other direction in the same way as a force can be resolved. Also, from the fundamental principle of the conservation of angular momentum, the axle of a gyroscope tends to remain in the same position it was placed provided no external forces act on it. However, if a free gyroscope is acted on by a torque in a plane through the gyro axis, then that axis will precess in another plane which is perpendicular both to the plane of the spin and to the plane of the torque.

The gyrostat is a gyroscope which has been balanced on its frame so that there is no torque and hence no precession. An instrument of this type was used as a stabilizer in the Brennan Monorail.

There are many applications of the gyroscope; such as in the gyrocompass and gyrostabilizer in marine usage, and as direction indicators, rate-of-turn indicators, automatic pilots, and gyroverticals in aeronautics. Sattinger and Therkelsen[50] in their instrumentation system developed for the measurement of terrain geometry make use of a vertical gyroscope as a measuring device.

d. An Instrumentation System for the Measurement of Terrain Geometry.[50] The required basic characteristics of a profile-measuring system include accuracy, economy, reliability, mobility, and usability of the form of the output data. There are several profile-measuring systems in use but those employing slope integration methods seem to provide the best results.

To function properly, a device based on the slope integration method is designed so that it mechanizes the equations:

$$Y - yo = \int_0^s \sin\theta \; ds, \text{ and}$$

$$x = \int_0^s \cos\theta \; ds$$

in which

s is the total distance traveled along the ground
Y is the elevation of the ground for total travel, s
yo is the elevation of the ground at the beginning of the run
x is the horizontal component of distance along the ground for total travel, s
θ is the slope angle of the ground under the vehicle at the distance s from the origin

For these equations, two quantities which must be measured continuously are the distance traveled by the vehicle and the slope of the ground over which the vehicle is traveling.

With a field equipment assembly for performing the measurement operation, continuous measurements are made of slope and surface travel by a trailer which is towed over the ground being measured. In the rear of the towing vehicle is housed the primary electrical instrumentation equipment and auxiliary devices (such as power supply, test equipment, and space components) and which accommodates an operator.

A conventional trailer hitch attaches the trailer which carries the primary instrumentation devices (figure B6). The trailer chassis is supported by a suspension on two automobile wheels of standard size. The slope of the ground is sensed by a pair of 11-in.-diameter wheels mounted in tandem on a 12-in. wheel base at the rear end of the assembly. An electrical contactor mounted on the leading wheel produces a voltage pulse at 2-in. increments of s , the travel of the wheel along the surface of the ground. The pitch angle of the measuring wheels is sensed by a vertical gyroscope mounted on the pivoted platform of the measuring assembly, total allowable range being from −90° to +90°. Coupled to the outer gimbal shaft of the gyro is the shaft of a photoconductive type of shaft-position-to-digital converter. The body of the converter is linked mechanically to the measuring wheel so that the device produces an electrical indication in digital form of θ , the angle of the wheel frame with respect to the horizontal. Seven binary digits are provided for, corresponding to a resolution of 1 part in 128 over a total angle of 180°.

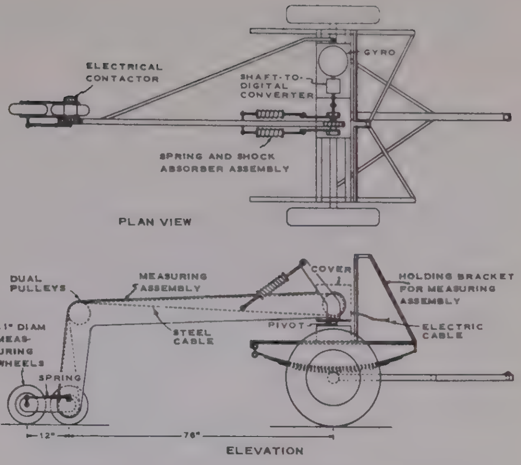

ELECTRICAL CONTACTOR
GYRO
SHAFT-TO-DIGITAL CONVERTER
SPRING AND SHOCK ABSORBER ASSEMBLY
PLAN VIEW
DUAL PULLEYS
MEASURING ASSEMBLY
COVER
HOLDING BRACKET FOR MEASURING ASSEMBLY
11" DIAM MEASURING WHEELS
STEEL CABLE
PIVOT
ELECTRIC CABLE
SPRING
12"
76"
ELEVATION

Figure B6. Trailer assembly of terrain geometry measurer
(From Sattinger and Therkelsen)

In operation, whenever a circuit is completed the electrical contactor mounted on the leading wheel of the trailer passes a pulse of current through the gas discharge lamp. This causes current pulses to occur at constant increments of advance of the wheel along the surface of the ground. Each pattern of pulse produced by the photoconductive cells on 7 output wires corresponds to the 7-bit number or ''character'' on the digital converter, representing θ at that instant. The voltage output of these wires is routed to a high-speed paper tape perforating system, and causes the 7-bit character representing θ to be punched into one position of the tape. The tape will be punched and advanced only when a new character is received from the converter. The advance of the paper tape is, therefore, proportional to the advance of the wheel along the ground and the tape becomes a record of θ vs s .

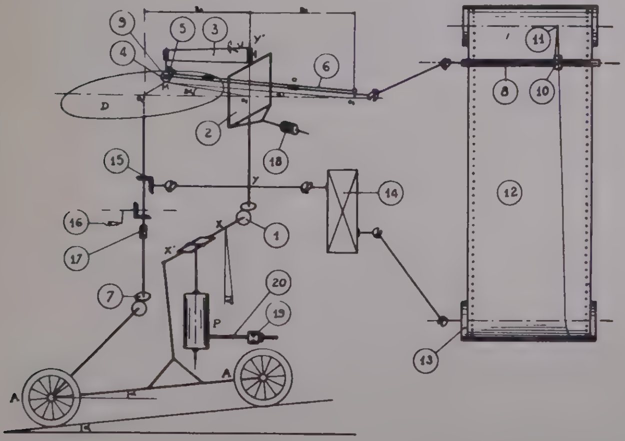


Figure B7. Schematic diagram of the clinodographe
(From Simonin)

e. ''Le Clinodographe.''

The clinodographe is a new instrument invented by Dr. Raymond F. Simonin. This device measures surface irregularities as well as profiles of the surface by means of a pendulum arrangement integrated mechanically.

The clinodographe is based on the principle that the wheel base is infinitely small compared to distance traveled. Figure B7 shows a diagrammatic sketch of this device. The pendulum, ''P'' is so arranged that only longitudinal translations are measured. Since the function of slope integration is integrated mechanically, a rotating disk ‘‘D’’ is connected to one of the wheels of the device.

As the rear wheel, ‘‘A’’ (figure B7), rolls over any curve of the pavement and drives disk ‘‘D’’ through a rigid transmission, roller ‘‘4,’’ which is the translating medium for the pendulum, rolls over its radius ‘‘r.’’ This in turn is transmitted through a stationary screw, ‘‘8,’’ which records the profile through a free-running nut on the paper. The paper is caused to rotate at a speed proportional to the drive wheels.

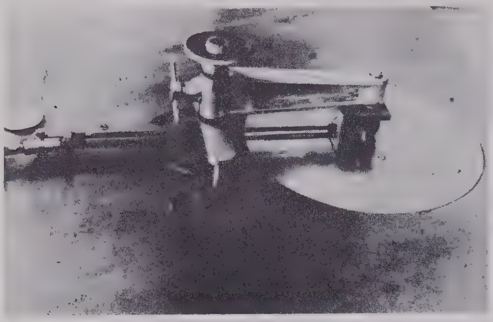


Figure B8. Integrator of the clinodographe
(From Simonin)

The small caster, ‘‘4,’’ is subjected to two motions, a rolling motion around its axis, and a sliding motion on the disk. This means of integration (figure B8) is quite common in that this principle has been used for obtaining variable speeds from a constant-speed motor. This principle is also analogous to that of the planimeter.

(1) Pendulum Oscillations. The principle just described gives a true profile only for the case where the pendulum is vertical. Since the pendulum does not stay vertical during horizontal movement, oscillations cannot be avoided.

Mathematically the only points to consider are those corresponding to a vertical position.

Let $V = \frac{ds}{dt}$ express the velocity of the chassis. The chassis then covers a distance equal to the unit of length of the trajectory within a length of time equal to

$$t = \frac{1}{V}$$

where t equals the time for one oscillation.

It is to be noted that the pendulum will cross the vertical plane twice during one oscillation. For this instrument the number of times true values are recorded are as given below:

$$x = \frac{2}{VT}$$

This device is so arranged that eight correct readings are given per meter of longitudinal profile.

(2) Road Roughness. A scanning wheel is placed in the center of the wheel base (figure B9). This is merely connected to a second stylus through a cable encased in a tube. This second stylus then records small surface irregularities that are not picked up by the main device.

(3) General Description. The clinodographe has no springs. Motorcycle tires inflated to a constant pressure at a wheel base of 2.50 m are used. The entire device is housed in a small, compact box protected from rain and dust.

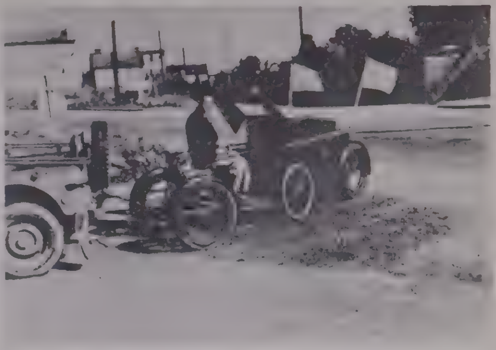


Figure B9. The clinodographe (From Simonin)

f. Sun Oil Company's Mobile Elevation Meter.[36] The elevation meter measures the difference in elevation between points on the earth's surface with an accuracy of a fraction of a foot in several miles. It has been used to provide vertical control for aerial surveys in topographic mapping, for establishing elevations for station sites for geological and geophysical exploration, but is limited in use by the fact that it can only traverse distances which can be covered by the towing vehicle.

The fundamental principle of operation on which the elevation meter is based is slope integration. If h_r is the difference in elevation between two points and the angle of inclination, θ_r, as well as the linear distance, $\Delta\ell_r$, are known, the following equation is obtained:

$$h_r = \Delta\ell_r \cdot \sin\theta_r \tag{1}$$

This computation is performed 500 times during every foot of travel over the surface, adding the increments of height (h_r) cumulatively as the survey proceeds upward above any given point or starting elevation. At points where the inclination is downward, the increments of (h_r) are negative, and are subtracted from the positive readings.

Consequently the total difference in elevation between any two points can be expressed mathematically as follows:

$$H = \Sigma\Delta\ell_r \cdot \sin\theta_r \tag{2}$$

Since $\Delta \ell_r$ is a function of velocity and time, it may be expressed as:

$$\Delta \ell_r = v \cdot \Delta t \tag{3}$$

Thus, the difference in elevation between points A and B becomes:

$$H = \Sigma\, v \sin \theta \cdot \Delta t \tag{4}$$

When the time interval over $\Delta \ell_r$ is small, Δt approaches zero, and the difference in elevation can be expressed as:

$$H = \int_A^B v \sin \theta \, dt \tag{5}$$

The time interval for each computation is quite small as can be seen by the fact that 14,667 computations per sec are performed when traveling at 20 mph.

The principal component of the elevation meter is a pendulum mechanism on a three-wheel, triangular-shaped trailer of special design. It furnishes an output signal which is proportional to the angle of inclination and is responsive only to changes in longitudinal inclination, and is insensitive to changes in transverse inclination. Output of the velocity generator is proportional to the unit's speed. An electric cable transmits the velocity signal to the towing vehicle.

Figure B10 shows an outline drawing of the component parts of the elevation meter. The trailer carries the pendulum and the velocity generator. The distance traveled over the earth's surface is recorded by a flexible cable drive geared to the rear trailer wheel which powers a mechanical counter. In turn, the velocity generator puts out a signal which is proportional to the velocity.

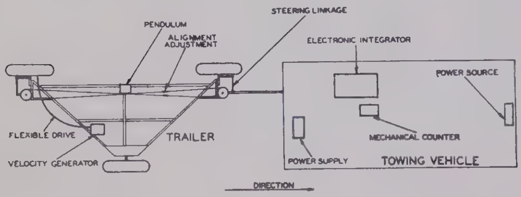


Figure B10. Component parts of elevation meter

(After Kastrop)

These two signals (one from the pendulum, the other from the velocity generator) are transmitted separately, via two independent electric cables, to the towing vehicle. Within the towing vehicle is mounted the electronic integrator which receives the two signals and integrates them according to formula 5. Results of the integration are shown on a relay-operated mechanical counter placed adjacent to the electronic integrator – the counter indicates changes of 1 ft.

Tenths of feet are indicated on an auxiliary electrical meter. The mechanical counter is also relay-operated and indicates the distance traveled in feet while an electric meter indicates tenths of feet.

A Leece-Neville system, driven by the towing vehicle engine, supplies the power necessary for all circuits of the elevation meter. The power supply which furnishes the various circuits with required voltages, current, and frequency is mounted in the trunk of the towing vehicle.

The measuring devices are mounted on a three-wheel trailer which is illustrated in outline form in figure B10 and by photograph in figure B11. The front and rear wheels are mounted on steel axles so they can be pivoted about the kingpin. The third wheel, located at the apex of the triangular frame, is permanently fixed in order that its axis of rotation is perpendicular to the center line between the pivot point of the front and rear wheels; it is also equidistant from front and rear wheels. The front and rear wheels are connected so as to turn together, but in opposite directions. Approximately 8 ft separates the front and rear wheels with the pendulum halfway between the two wheels. Theoretically the base length should be as small as possible for maximum precision.

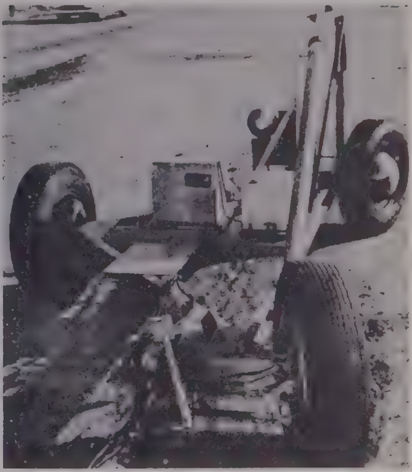


Figure B11. Sun Oil Company elevation meter
(After Kastrop)

The motion of the pendulum is always at right angles to the turning radius of the trailer and, therefore, the instantaneous direction of the trailer is in the plane of the pendulum motion. As a result of the three-point support, the front and rear wheels will always be in contact with the road. The rear wheel exactly tracks the front wheel, placing the pendulum at the tangent point on an arc of the turn. Errors due to transverse slope are avoided by having the plane of motion of the pendulum parallel to the direction of tow.

To calibrate the meter, the pendulum is placed on a tilt stand and adjusted to an angle of 15 degrees plus and 15 degrees minus. While in these respective positions, a standard velocity signal is supplied to the integrator. A short run of one minute is made and if the answer is incorrect, an adjustment is made.

It is necessary that a standard cell be compared continuously with a reference voltage in the system because the integrator is electronic. Should the latter voltage vary, the circuit is so designed that an automatic correction is made. It has been determined that the error varies as the square root of the distance.

g. Principles of Photogrammetric Techniques (Personal Correspondence With Prof. R. F. Baker). This procedure has not been developed fully at the present time (January 1958). It would involve the use of a stereoplotter to make measurements over relatively large areas to the accuracy of 0.01-ft elevation.

Before this procedure can be adopted it will be necessary to study the feasibility of obtaining photographs by helicopter at elevations up to 200 ft above the runway and at lower elevation off the edge of the runway.

Possible data would include a profile along the center line and the other contours from a checker-based type of data. It would be necessary to establish at least three central points per photograph.

Date Due

JAN 29 '79
APR '84
4713
ALP
Parc

PAM 629.139.85' TechrepT13

University of Alberta Library
0 1620 0336 7792